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This is the final progress report of teh vision group at the University of Texas under support of AFOSR URI grant F49620-93-1-0307. In this report we will attempt to summarize the major accomplishments over the previous 5 years. Aim 1: to develop a mathematical model of the initial stages of visual processing (the front-end mechanisms), based upon a wide range of physiological and psychophysical data. Aim 2: To develop new methods and models of local frequency coding. Aim 3: To develop new mathematical models and computer-vision algorithms for performing complex visual tasks that are based upon local frequency coding representations. Aim 4: To develop models for human performance in complex visual tasks that build upon current understanding of the front-end mechanisms. Aim 5: To develop a computational testbed for implementing, comparing, integrating and visualizing the different models and modules developed during the project, using a massively parallel machine and graphics workstation front-end.

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Local Spatio-temporal Analysis in Vision Systems: Final Technical Report

AFOSR F49620-93-1-0307

August 1, 1997 to May 31, 1998

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Introduction

This is the final progress report of the vision group at the University of Texas under support of AFOSR URI grant F49620-93-1-0307. This year we have been operating under a no cost extension of the grant. Because a relatively small amount of funds were carried over into this year, progress on the specific aims of the proposal were less this year than in previous years. In this report we will attempt to summarize the major accomplishments over the previous 5 years.

Before presenting the technical details, we mention several related developments that have been a direct result of the URI grant.

(a) The interdisciplinary Center for Vision and Image Sciences (CVIS), was formed as a direct consequence of the URI grant. The Center was awarded renovated space (in addition to the existing research space of the Center faculty). Further, construction of a new $42M Psychology building will begin shortly. In the current architectural plans, the Center has been given approximately 1000 sq. ft. of very nice space (in addition to the research space for the Center faculty). The URI grant has also served as a key factor in the acquisition of additional research space and equipment from the Departments of Psychology and Electrical and Computer Engineering.

(b) A number of research grants from NIH and DOD have been submitted through the Center and are now being administered through the Center.

(c) The University of Texas has provided some funds to the Center for equipment, and for administrative staff, in the form of returned overhead.

(d) The Center has expanded to include new faculty (Todd Maddox and Brian Evans), and has attracted a visiting scholar (Bruce Henning from University of Oxford) who was at the Center this year.

(e) The URI grant has fostered increased interactions between faculty and students in the Department of Psychology, the Department of Electrical and Computer Engineering, and the Biomedical Engineering Program. The nature and depth of some of these interactions is apparent in this progress report.

Objectives

Aim 1: *To develop a mathematical model of the initial stages of visual processing (the front-end mechanisms), based upon a wide range of physiological and psychophysical data.*

Aim 2: *To develop new methods and models of local frequency coding.*

Aim 3: *To develop new mathematical models and computer-vision algorithms for performing complex visual tasks that are based upon local frequency coding representations.*

Aim 4: *To develop models for human performance in complex visual tasks that build upon current understanding of the front-end mechanisms.*

Aim 5: *To develop a computational testbed for implementing, comparing, integrating and visualizing the different models and modules developed during the project, using a massively parallel machine and graphics workstation front-end.*

Accomplishments / New Findings

Publications, submitted papers, conference presentations and technical reports are listed at the end of the progress report. Copies of some of the relevant written material since the last progress report are appended.

I. Aim 1: *To develop a mathematical model of the initial stages of visual processing (the front-end mechanisms), based upon a wide range of physiological and psychophysical data.*

A. *Albrecht's Laboratory*

During the project period Albrecht, Geisler and students have made very substantial progress in developing a general model of single neuron responses in the primary visual cortex of the macaque monkey. The model contains four major components: contrast gain, linear filter, expansive exponent, internal noise. This combination of linear and nonlinear components, arranged in a particular sequence, accounts for much single unit data and reveals many interesting and unexpected aspects of how visual cortex neurons transmit, extract and encode information about objects in the environment. This model has been widely cited and tested by researchers in other laboratories.

Albrect, Geisler and students have also developed important new methods for characterizing the information processing properties of single neurons and populations of single neurons. Specifically, they developed (for the first time) a precise Bayesian method (the *descriptive function method*) for measuring the feature identification performance of single neurons, and the discrimination performance of entire populations of single neurons.

Albrecht, Geisler and students have made many new quantitative measurements of the responses of single neurons in the primary visual cortex of the macaque monkey. The studies included precise quantitative measurements of tuning functions along various stimulus dimensions, of response noise characteristics, of the effect of contrast on spatio-temporal phase, and of the effects of naturalistic temporal stimulus presentation. All of these studies revealed important general systematic properties of cortical neurons which have made important contributions to the development of the general model.

A readible summary of the work carried out by Albrecht and Geisler under the AFOSR URI grant is given in a chapter which will appear in the *Handbook of Cognition and Perception* (enclosed).

B. *Cormack's Laboratory*

During the project period Cormack and students have made significant progress toward understanding of the effects of early filtering on binocular vision and stereopsis. Progress was made through both human behavioral studies and computational modeling. Areas in which the most progress was made include the theoretical efficiency of stereopsis, the influence of spatial frequency channeling on stereopsis, and the nature of depth encoding. Estimates of the efficiency of stereopsis were established using an ideal observer applied to the binocular random noise stimuli. These experiments established estimates of the limiting sampling density and information capacity of the binocular visual system. More surprisingly, they revealed that early binocular integrating areas are not fixed, but seem to be able to adjust in space-time to achieve maximum efficiency for the task at hand.

C. *Geisler's Laboratory*

During the project period, Geisler and students have made substantial progress in developing a general model of human pattern detection and a general model of pattern discrimination. A key feature of the models is that that they are strongly constrained by the known anatomy and physiology of the human/primate visual system. Specifically, the models consist largely of anatomically and physiologically determined mechanisms, followed by an optimal (Bayesian) decision rule. Thus, the models have almost no free parameters. By being closely tied to the anatomy and physiology of the primate visual system, the models provide a stronger link between psychophysics and neurophysiology than previous pattern vision models, and they have an excellent chance of being able to predict performance under a wider range of novel circumstances.

There are two versions of the model. The first version (which is designed for detection) contains the following components: (1) the optics of the eye (based on objective measurements in humans), (2) the human ganglion cell distribution across the retina (based on the anatomical measurements in humans), (3) the

macaque ganglion-cell receptive-field shapes (based upon the electrophysiological measurements), (4) the macaque cortical contrast-response nonlinearities (based upon the electrophysiological measurements), (5) the macaque cortical neural noise characteristics (based upon the electrophysiological measurements), (6) a (maximum-likelihood) decision rule which optimally pools the responses of all the neurons. This model predicts a range of psychophysical data quite accurately, suggesting that the anatomical and physiological mechanisms included in the model are the ones most responsible for determining human detection performance under steady background conditions.

The second version of the model (which we call a *neuron sampling model*) is similar to the first, except for the inclusion of cortical receptive field shapes. Our approach has a new unique feature not contained in other spatial vision models. Rather than representing cortical spatial coding as a small set of spatial-frequency and orientation-tuned channels (i.e., just a few different receptive field shapes), we take into account the true heterogeneity of the cortex. Specifically, we use actual electrophysiologically measured distributions (histograms) for the center spatial frequency, center orientation, spatial-frequency bandwidth, orientation bandwidth, etc. to construct a truly heterogeneous (and hence realistic) sample of cortical neurons. Because there is something on the order of 100 times as many primary cortex neurons as ganglion cells, it is not feasible to build a model which represents every cortical neuron. However, by randomly sampling from the measured distributions, we can create a large, statistically-accurate sample (e.g., several hundred thousand neurons). The predictions for such a sample match that for a complete set of neurons, except for a scale factor on threshold (more precisely, a scale factor on d'). This model generalizes the first version by allowing predictions for pattern discrimination. The model predicts the contrast discrimination functions and spatial frequency discrimination functions reasonably well (without free parameters). An interesting exception is that the model does not predict the "dipper effect" seen in contrast discrimination functions. These results point to the importance of the heterogeneity of the cortex in determining human discrimination performance, and that the dipper effect is probably due to mechanisms beyond primary visual cortex (contrary to the current viewpoint).

II. Aim 2: Develop new methods and models of local frequency coding.

A. *Bovik's Laboratory*

Bovik and students have developed the general theory and computation of very general *image modulation models*, whereby image contrast and phase structures in image data are modeled as amplitude- and frequency-modulated (AM & FM) sinusoidal functions, and especially, as sums of such functions. The approach broadly generalizes the sinusoidal models commonly used both in studies of biological visual perception (e.g., the spatial-frequency channel models, and the so-called "energy" models of spatio-temporal vision), and also in engineering analysis of digitized images (e.g., the Discrete Fourier Transform). They have shown the new image model to be quite powerful for a variety of important applications, including analyzing nonstationary image structures; segmenting

nonstationary textured images; computing object shape from monocular images; computing depth from binocular images by stereoscopic matching of image modulations; image compression via the "AM-FM Transform," and classification and recognition of digitized fingerprints via AM-FM modeling. They have also successfully fused the AM-FM model with wavelet-based methods for modulation extraction, and we have proposed the AM-FM model as a possible mechanism for local/global modeling of visual data in biological vision systems.

This work and its offshoots has resulted in numerous high-profile image processing journal publications, and it has resulted in the graduation of a several PhD students working on AM-FM problems: Joseph P. Havlicek, currently Assistant Professor at the University of Oklahoma, Norman, OK; Boaz S. Super, currently Assistant Professor at the University of Illinois, Chicago; Terry Chen, currently Research Scientist at the Chung-Shan Institute of Science and Technology in Taiwan; Dong Wei, currently Assistant Professor at Drexel University in Philadelphia, PA; and Marios Pattichis, currently Assistant Professor at Washington State University, Pullman, WA.

III. Aim 3: Develop new mathematical models and computer-vision algorithms for performing complex visual tasks that are based upon local frequency coding representations.

A. ***Bovik's Laboratory***

FOVEA: Foveated, Fixating Stereo Active Vision System.

Bovik and students have successfully developed the theory, algorithms, hardware realization, and benchmark testing of a unique, state-of-the-art foveated and fixating active stereoscopic vision system with computer-controlled vergence, baseline adjustment, pan, tilt, and focus control. The successful implementation of a graded resolution hierarchy emanating from a central fovea into a truly participatory active vision system (which is a first) has made it possible to place the burden of obtaining detailed, high-resolution scene information on the design of fixation, vergence and focusing strategies. In FOVEA, dense 3-D scene representations are obtained by introducing multiple fixation points, which are subsequently integrated, making computation efficient and well-posed. Alternative approaches which are based upon massive, single-frame number-crunching are vastly less efficient and are ill-posed.

Construction of the FOVEA platform entailed the design and development of a foveated active vision system that is fully software-controllable. FOVEA allows the expert program to combine hardware and software protocols for computer feedback-controlled variable baseline vergent stereo, and for lens parameter control (including zoom, software foveation, depth-from-focus, and dynamic aperture control). They have designed and implemented software foveation protocols, whereby the degree of foveation is controlled according to the scene characteristics; they designed methods for estimating 3-D range from defocus information by using active focus control to directly estimate the depth of points or regions in a scene; they developed freeform visual fixation algorithms whereby the

cameras are directed towards regions of interest combined with a semi-random fixation strategy that explores the entirety of the scene with particular emphasis on high-information features; they developed a foveation-driven stereo camera vergence strategy which is ideally suited for efficiently computing depth vergent (non-parallel) cameras, using the observation that the tradeoff between matching complexity (highest near the periphery in a vergent system) and depth resolution (lowest near the periphery in a foveated system) be made explicit in a natural way; and they demonstrated all of these many facets of work in a fully functional, on-line series of demonstrations of FOVEA that effectively highlight FOVEA's provocative capabilities and potential for future development and application.

The results of this work have been published in a series of high-profile journal papers and the work has resulted in two PhD dissertations being completed: Changhoon Yim, currently a Research Engineer at David Sarnoff Research Center, Princeton, NJ, and William Klarquist, currently a Research Engineer at SAIC, Denver Colorado.

B. *Ghosh's Laboratory*

Ghosh and students have made considerable progress working out the implications of artificial foveated vision for a variety of engineering applications. These studies also quantified the computational implications and advantages of foveated processing. Major results include emergence of innovative non-uniform resolution techniques for pattern analysis and classification, and a detailed implementation of an artificial foveated system using retinal and ganglion sampling/receptive field data from primates, and showing its impact on different imagery, particularly those involving texture segregation.

Equally important work has involved the investigation of neural network approaches to various pattern recognition and learning processes related to human and artificial vision. Fundamental contributions were made to the theory and applications of localized receptive field based networks, and to the theory of network ensembles for better and more robust pattern recognition, leading to several full-length journal papers.

C. *Super's Laboratory*

During the project period, Super developed models to capture the relationship between the local spatial frequency decompositions of surface patterns and their corresponding image patterns, as a function of the surface geometry and the projection process. These models were successfully used to develop algorithms for recovery of 3D surface orientation and shape from analysis of image texture ("shape-from-texture"). A variation of the model that included sampling effects was used for simultaneous recovery of surface depth and orientation from stereopsis. The stereo algorithm was designed to operate under conditions, such as wide baseline and short object distance, that are considered difficult for traditional stereo algorithms because of the large inter-image distortions

induced. The stereo model was also used to study the interaction of photoreceptor mosaic sampling effects with stereo viewing geometry in the human visual system's binocular apparatus.

IV. Aim 4: *Develop models for human performance in complex visual tasks that build upon current understanding of the front-end mechanisms.*

A. *Cormack's Laboratory*

Cormack and students completed a series of experiments on the influence of early spatial frequency filtering in stereovision. They established the existence of some very interesting spatial frequency interactions in the binocular visual system. In short, it was revealed that the binocular visual system takes advantage of information present in different spatial frequency channels to resolve ambiguities that arise in matching the two eyes' images. A computational model was developed that accounted for the data and predicted some novel results.

A series of experiments was also done in order to investigate the manner in which the depth signal is encoded by the visual system beyond the site of binocular combination. These experiments revealed a critical dependence on the temporal aspects of the stimuli, and indicate that there may be two parallel systems for encoding depth, one with very transient temporal properties and another that is more sluggish. A computational model of depth encoding with these properties was developed and predictions from the model are being tested in ongoing experiments.

B. *Geisler's Laboratory*

During the project period Geisler and students developed a theoretical approach and an experimental method for assessing (and hence isolating) the role of low-level factors in complex tasks. The method involves comparing simple-discrimination performance and visual search performance for the same stimuli. Analysis of the results showed that much of the variation in (multiple fixation) search time was predictable from the discrimination data, suggesting that low-level factors often play a dominant role in limiting search performance. They also developed a signal-detection model which demonstrates how current psychophysical models of visual discrimination might be generalized in order to obtain a quantitative theory that can predict visual search performance under a wide range of stimulus conditions. A new real-time method of controlling the information across the visual field during active search was inspired by this work. Specifically, under another AFOSR proposal Geisler and students developed real-time software that runs on a PC and can be used to dynamically modulate the spatial frequency content of arbitrary static or video imagery contingent upon eye position measured with an eye tracker. This software has great potential for the study of visual search.

In a related line of research, Geisler, Super and students have explored how local spatial information extracted by the primary visual cortex is combined to find the

spatial structure that exists in 2-D images (an ability that is very well-developed in the human visual system). Geisler, Super and students have developed, and tested in psychophysical experiments, a computational model that incorporates most of the known grouping rules within a single coherent framework. This model addresses many aspects of perceptual organization not addressed by previous models.

C. *Gilden's Laboratory*

During the project period Gilden and students have been involved in two main areas of research. The first concerns the nature of the fluctuations in performance that occur in various perceptual and cognitive tasks (mental rotation, lexical decision, parallel visual search, and serial visual search). They find that a substantial fraction of the residual variability, and this generally exceeds 90% of the total variance in individual subjects, is described by a 1/f noise distribution. 1/f noise refers to a signal that has a power spectrum that is inversely proportional to frequency and is thought to be produced in self-organizing critical systems. These findings may have a wide impact upon the development of models for perceptual estimation in many stimulus domains.

The second area of research concerns motion perception. Gilden has developed a theory of motion perception based on mathematical and visual constraints on the formation of frames of reference. One implication of the theory is that if and only if a motion field can be fully represented by diagonal energy in space-time can it be processed preattentively. Only translation fields satisfy this requirement. Rotation fields, for example, require spatial distinctions with respect to the axis of rotation, in addition to the specification of local speed; e.g., clockwise rotation has the upper part of the field moving right and the lower part of the field moving left. For homogeneous translation fields there is no local specification of spatial concepts such as upper and lower. Gilden has tested the theory in a large series of experiments by measuring memory and search performance for translating, rotating, and diverging (expanding or contracting) stimuli. The theory is largely supported although there are some interesting twists. The major results are as follows: (1) There is good memory for speed of translation independent of speed, but there is poor memory for rotational speed except for slower rotations. (2) There is good memory for direction of translation and divergence, but very poor memory for direction of rotation so long as the axis of rotation is contained within the object. (3) If the rotation axis is external to the object then there is significant memory for clockwise rotations, but very poor memory for counterclockwise rotations. (4) In careful search experiments it appears that rotation direction is subject to a limited capacity parallel search, whereas translation direction is more characteristics of unlimited capacity parallel search.

D. *Super's Laboratory*

Super and Geisler (1) developed a theoretical framework for perceptual organization, (2) carried out a series of experiments on human subjects to quantitatively measure perceptual grouping behavior in the human visual system (HVS), and (3) developed a computational model of perceptual

grouping behavior in the HVS. Additionally, Super has developed a preliminary architecture for multi-level grouping (grouping which involves interactions across levels in the grouping heirarchy) in computer vision systems. This research led to a new method for cluster selection in hierarchical cluster analysis in the field of pattern recognition.

V. Aim 5: Develop a computational testbed for implementing, comparing, integrating and visualizing the different models and modules developed during the project, using a massively parallel machine and graphics workstation front-end.

A. *Ghosh's Laboratory*

Ghosh and students have completed work on forming a suite of computational vision algorithms as well as programs related to modeling the human visual system. These algorithms have been implemented on the 4K processor MasPar MP-1, and used for various empirical studies. For example, based on the retinal filter of Geisler and current knowledge of ganglion sampling and receptive field parameters, they have done extensive studies on texture discrimination using a foveated front-end model of the human retina.

Personnel Supported

Principal Investigators

Wilson Geisler
Alan Bovik
Duane Albrecht
Joydeep Ghosh
David Gilden
Lawrence Cormack
Boaz Super

Technical Support Personnel

Carl Creeger
Larry Stern
Alison Crane Tannenbaum

Administrative Support Personnel

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Direct Research Personnel

Students

Kurt Bollacker
Joseph Havlicek (graduated with Ph.D)
Viral Kadakia
William Klarquist (graduated with Ph.D)
Turker Kuyel

Xiaonong Li
David Landers
Hung-Ta Pai
Sangho Park
Marios Pattichis
Christy Price
Vishwanath Ramamurthy
Bryan Stiles
Tom Thornton
Dong Wei
Changhoon Yim (graduated with Ph.D)
Robert Frazor
Caden Schafer
Cecily Anders
Terry Chen (graduated with PhD)
Dave Harding
Jeff Wehnes
Kartick Subramanian (summer 1997)

PUBLICATIONS

Publications marked * are appended.

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1993 Conference Presentations / Talks / Technical Reports

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179. Frazor, R.A., Albrecht, D.G., Geisler, W.S. and Crane, A.M. (1998). Discrimination performance of v1 neurons in monkeys and cats for different intervals of integration. *Investigative Ophthalmology & Visual Science Supplement.* (ARVO) 39/4, S238.

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183. Lee, S. and Bovik, A. C. (1998). Maximally flat bandwidth allocation for variable bit rate video. *IEEE International Conference on Image Processing,* Chicago, IL.

184. Lee, S. and Bovik, A. C. (1998). Rate control for foveated MPEG/H.263 video. *IEEE International Conference on Image Processing,* Chicago, IL.

185. Lee, S., Pattichis, M. S. and Bovik, A. C. (1998, October). Foveated image/video quality assessment in curvilinear coordinates. *International Workshop on Very Low Bitrate Video Coding,* Urbana, IL.

186. Thornton, T. and Geisler, W.S. (1998). Texture segregation on the basis of local shape information. *Investigative Ophthalmology & Visual Science Supplement.* (ARVO) 39/4, S649.

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188. Wei, D., Pai, H.-T. and Bovik, A. C. (1998). Antisymmetric biorthogonal coiflets for image coding. *IEEE International Conference on Image Processing,* Chicago, IL.

INVENTIONS / PATENTS

None

HONORS / AWARDS

1998	Bovik: Recipient of the IEEE Signal Processing Society Meritorious Service Award.
1998	Bovik: Continued as the Editor-in-Chief, *IEEE Transactions on Image Processing*.
1998	Bovik: Named to the Editorial Board of the *The Proceedings of the IEEE,* which is the main journal of the largest technical/scientific society in the world.
1998	Bovik: Continued as Member of the Board of Governors of the IEEE Signal Processing Society.
1998	1998 Geisler named Section Editor of Vision Research.

1998	Ghosh: Plenary Presentation, *SPIE Conf. On Applications and Science of Computational Intelligence*, Orlando.
1998	Ghosh appointed Letters Editor, *IEEE Trans. Neural Networks.*
1997	Cormack was nominated by the University of Texas for Presidents Young Investigator Award.
1997	Ghosh awarded Best Application Paper, Artificial Neural Networks in Engineering (ANNIE'95) Conference, for "Image Enhancement using Scale-based Clustering Properties of the Radial Basis Function Network."
1997	Ghosh was keynote speaker, ANNIE'97, St. Louis.
1997	Ghosh received Dean's Fellowship, University of Texas.
1997	Viswanath Ramamurti, Ph.D completed: "Structurally Adaptation and Generalization in Modular Neural Networks", August, 1997 (Technology Resources Inc (research division of SBC Corp.), Austin)
1997	Geisler received one of two campus-wide Career Research Excellence Awards given for the first time this year by the University of Texas at Austin.
1995	Geisler named to Editorial Board of Vision Research.